Electron Spin Flow and Transport in Semiconductor Epilayers

Darryl L. Smith, T-11; M. Hruška, Lawrence Livermore National Laboratory; Š. Kos, Cambridge University; Avadh Saxena, T-11; and S.A. Crooker, MST-NHMFL

A new generation of electronic devices, with the potential to outperform conventional electronic circuits in speed, integration density, and power consumption, has been proposed based on the ability to manipulate electron spin in semiconductors. To design semiconductor structures whose function is based on electron spin, it is necessary to understand spin dynamics and spin-polarized transport, and in particular, how they are affected by electric, magnetic, and strain fields. Spin dynamics and spin transport in semiconductors have been studied experimentally using time- and/or spatially-resolved spin-sensitive optical spectroscopies based on the magneto-optical Faraday and Kerr effects [1, 2]. We have microscopically derived an equation of motion for the electron Green's function that gives a full quantum-mechanical description of electron spin dynamics and transport in the presence of electric, magnetic, and strain fields. From this equation of motion we constructed a semiclassical kinetic theory of electron spin dynamics and transport in the presence of these fields [3, 4]. From the semiclassical kinetic theory, we derived a set of spin-drift-diffusion equations for the components of the spin density matrix for the case of spatially uniform fields and electron density. We solved the spin-drift-diffusion equations numerically and found good agreement with scanning Kerr microscopy images of spin-polarized conduction electrons flowing laterally in bulk epilayers of n-type GaAs. We contrast the effects of magnetic and strain fields on electron spin transport.

Figure 1 shows schematics of the two experimental geometries. A [001]-oriented n:GaAs epilayer sample, whose surface normal is along the z-axis, is subject to in-plane electric and magnetic fields, as well as strain fields. As illustrated in Fig. 1a, the sample may be optically excited by a circularly polarized laser beam propagating along the surface normal so that electrons, spin polarized along the z-axis, are optically injected. Alternatively, spin polarized electrons may be electrically injected into the semiconductor from ferromagnetic contacts as illustrated in Fig. 1b. For electrical injection, the injected electron spin polarization follows the magnetization **M** of the ferromagnetic contact, and is, therefore, typically in the x-y plane of the sample surface (for certain special ferromagnetic contacts both **M** and the injected electron spin polarization may be directed along the surface normal). The spin polarized electrons subsequently drift and diffuse in the x-y sample plane. The epilayer, in which the electrons are confined, is thin compared to a spin diffusion length so that the spin density is essentially uniform in the z-direction. The resulting steady state spin polarization is imaged via scanning Kerr microscopy, which is sensitive to the z-component of electron spin polarization, n_z. In the experiments, ohmic side contacts allow for a lateral electrical bias (E_x) in the x-y plane, Helmholtz coils provide an in-plane magnetic field (B_y),

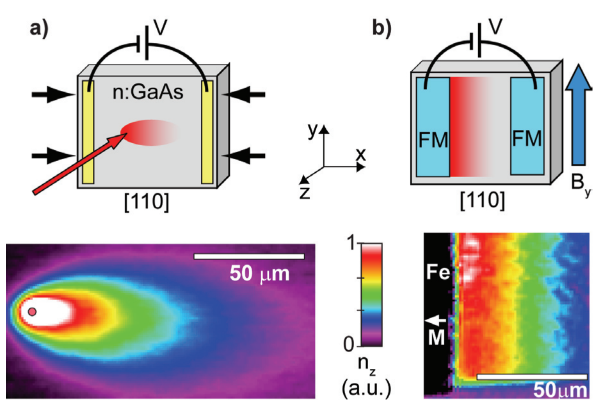

Fig. 1. *Schematics of the two experimental geometries.*

and uniform off-diagonal strain (ε_{xy}) is provided by a controlled uniaxial stress applied to the sample along a [110] crystal axis. The experimental data in the lower panels of Fig. 1 show false color 2-D images of the measured z-component of electron spin polarization, showing the flow of spin polarized electrons. In the lower left panel, spin-polarized electrons are optically injected using a laser focused to a 4 μm spot (illustrated by the circular red dot) and these spins subsequently diffuse and drift to the right in an applied electric field ($E_x = 10$ V/cm). In the lower right panel spin-polarized electrons are electrically injected from an iron tunnel-barrier contact that is magnetized along $-x$. The injected spin polarization is in the x-direction, and a small magnetic field in the y-direction ($B_y = 3.6$ G) rotates the spins so that there is a z-component of spin polarization that can be detected by Kerr microscopy.

In Fig. 2 we compare our calculations with experimental results for the case of optical spin injection with the data obtained via scanning Kerr microscopy. In these measurements, a linearly polarized narrowband Ti: sapphire laser, tuned just below the GaAs band-edge and focused to a 4 μm spot on the sample surface, was raster-scanned in the x-y sample plane to construct a 2-D image of n_z. The sample was a Si-doped n-type GaAs epilayer (electron density = 1 x 10^{16} cm^{-3}) grown on a [001] oriented semi-insulating GaAs substrate. Spin polarized electrons were optically injected into the sample by a separate, circularly-polarized 1.58 eV diode laser that was also focused to a 4 μm spot on the sample. Measurements were performed at a temperature of 4 K. Figures (a), (c), and (e) compare calculated and measured results for spin flowing to the right in the presence of uniform off-diagonal strain ($\varepsilon_{xy} = 4 \times 10^{-4}$; $E_x = 12$ V/cm), while Figs. (b), (d), and (f) compare calculated and measured results for spins flowing to the right in the presence of an applied magnetic field ($B_y = 16$ G; $E_x = 7$ V/cm). There is very good agreement between theory and experiment. The material parameters used in the calculation were: mobility $\mu = 3000$ cm2/Vs, spin relaxation time $\tau_s = 125$ ns, and diffusion constant $D = 10$ cm^2/s. We used a value of $C_3 = 4.0$ eVÅ for the spin-strain coupling coefficient based on previous experiments. Both strain and magnetic field lead to precession of the electron spins. However, the spatial damping of the precession is more pronounced when magnetic rather than strain fields are applied (at the same precession length).

For more information contact Darryl Smith at dsmith@lanl.gov.

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[2] S.A. Crooker, et al., *Science* **309**, 2191 (2005).
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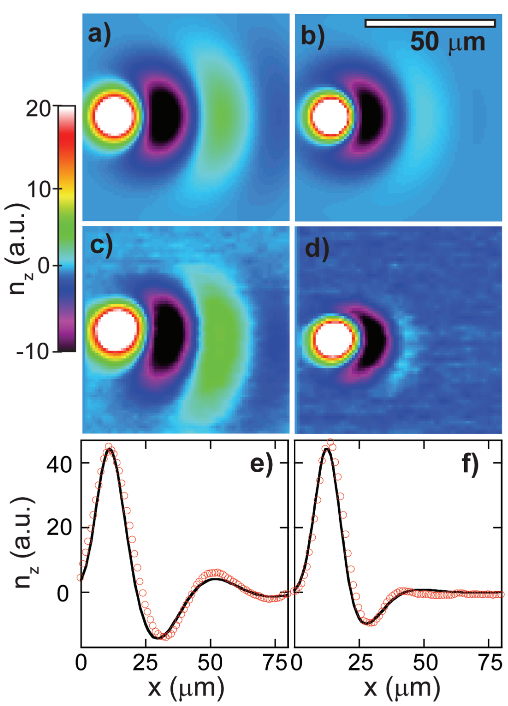

Fig. 2.
Our calculations compared with experimental results for the case of optical spin injection with data obtained via scanning Kerr microscopy.